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Effects of Aircraft Windscreens and Canopies on HMT/D Aiming Accuracy: Part 3

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ABSTRACT

Modern fighter aircraft windscreens and canopies are typically made of curved, transparent plastic for improved aerodynamics and bird-strike protection. Since they are curved these transparencies often refract light in such a way that a pilot looking through the transparency will see a target in a location other than where it really is. This effect has been known for many years and methods to correct the aircraft head-up display (HUD) for these angular deviations have been developed and employed. The same problem occurs for helmet-mounted display/trackers (HMD/Ts) used for target acquisition. However, in this case the pilot can look through any part of the transparency instead of being constrained to just the forward section as in the case of the HUD and his/her head position can be anywhere in a rather large motion box.

To explore the magnitude of these aiming errors several F-15, F-16, F-18, and F-22 transparency systems were measured from a total of 12 different eye positions centered around the HMD Eye (the HMD Eye was defined to be a point 1.25 inches to the right of the aircraft Design Eye). The collection of eye points for assessing HMT/D aiming accuracy were: HMD Eye, 3 inches left and right of HMD Eye, 2 inches above HMD Eye, and 2 inches forward of HMD Eye plus all combinations of these. Results from these measurements along with recommendations regarding means of assessing "goodness" of correction algorithms are presented.

Keywords: helmet mounted displays, aircraft windscreens, aiming accuracy, aiming error, angular deviation, canopies, cueing systems

1. INTRODUCTION

A visually-coupled system (VCS) is composed of a head/helmet tracker, a head/helmet mounted display, and, in the case of the aircraft application, a sensor that can be slewed in a direction indicated by the tracker. This helmet mounted tracker and display (HMT/D) system can be used as a cueing device to direct a separate, aircraft-mounted sensor to point in the same direction as determined by the tracker. If the system were perfect, the sensor would point in exactly the same direction as determined by the HMT/D. However, the sensor has a direct view of the target area whereas the observer sees the target area through a windscreen or canopy. Aircraft transparencies may refract light in such a way as to make the target appear in a location other than where it actually is. This refraction effect is called "angular deviation" which is the angular deflection suffered by a light ray as it passes through the transparency. The objective of the effort described in this paper was to determine the angular deviation that could be expected for F-15, F-16, F-18, and F-22 transparency systems. For purposes of clarity it should be noted that the aircraft transparency system for F-15 and F18 aircraft is composed of two parts: the windscreen (which is the transparency in the forward part of the aircraft which does, indeed, serve to block the wind) and the

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canopy (which is the part that typically goes over the head of the pilot and is the part that can be opened to allow the pilot to get in and out of the aircraft). For the F-16 and F-22 aircraft there is only one transparency and it serves as both windscreen and canopy.

2. APPROACH

2.1 Data collection

Because aircraft windscreens and canopies vary somewhat from unit to unit (manufacturing tolerances) and because it is exceedingly difficult to reliably calculate the angular deviation of these transparencies from descriptions of the intended transparency shape it was decided to directly measure several transparency systems (windscreen and canopy) for each aircraft type of interest. This included F-15, F-16, F-18, and F-22 aircraft. It should be noted that there may exist serveral windscreen designs for each aircraft making this approach a bit more difficult. Nevertheless, several transparencies of different designs were obtained for each aircraft type to explore the general distribution and magnitude of angular deviation. A total of six F-15 windscreens (four advanced design windscreens (ADWs) and two older acrylic design) and four canopies (two single seat and two dual seat versions) were obtained for F-15 transparency system measurement. For F-18 two new E/F windscreens and three older acrylic night attack windscreens, two single-seat canopies, three forward two-seat canopies and one aft two-seat canopy were used. For the F-16 a total of six canopies were obtained from two manufacturers (three from one manufacturer and three from another). For F-22 a total of four canopies from a single manufacturer were measured (at the manufacturer's facility). Measurements of angular deviation of aircraft windscreens for HUD corrections are normally done with respect to the design eye position. The design eye position is nominally where the pilot would position his single Cyclops eye (if he had only one eye located halfway between his eyes). For this activity, an HMD eye position was defined as being a point 1.25 inches to the right of the design eye. This corresponds to a monocular HMD with the display located in front of the right eye. Angular deviation measurements were then made from a total of 12 eye positions consisting of all combinations of HMD eye, 2 inches forward of HMD eye, 2 inches up from HMD eye, and 3 inches either side of the HMD eye. This modest size motion box of 2x2x6 inches was dictated by the limitations of the windscreen movement table measurement system.

The field angles that could be measured from these 12 eye positions were also limited by the range of movement of the windscreen table in elevation and azimuth and the effects of the coordinate conversion equations [5]. With the original windscreen movement table we were limited to measuring field angles defined by the box located around the zero-azimuth, zero-elevation position in Figure 1 (the inverted "U" shape inside this box corresponds, approximately, to the field angles associated with the F-15 windscreen only). Since pilots wearing an HMT/D could easily direct their angle of gaze to a substantially wider range of angles than that covered by this limited box, it was necessary to modify the measurement equipment to accommodate a wider range of angles. This was done by changing the physical placement of the measurement equipment. Figure 2 is a photograph of the system as it was originally configured to measure F-16 and F-15 windscreens. Figure 3 is a photograph of how the equipment was modified to measure zone 3 (nominally around the 40 degrees elevation zone; an F-16 transparency is on the table). Mounts were made to make measurements at 20, 40, and 60 degrees elevation as indicated by the upper three dark lines in Figure 1 (with labels of 20, 40, and 60). Originally [5], other elevation angles were measured in the vicinity of these 3 angles and converted to the appropriate coordinate system as described in Task and Parisi (1997). It was discovered, however, that these extra data points did not noticably change the goodness of the models developed to fit the data so measurements were limited to the 20, 40, and 60 degree elevation scans and the box measurements only. The lower three dark lines of Figure 1 (labeled A, B, and C) correspond to data that was collected on a few of the canopies using a very crude movement table in order to investigate angular deviation in these areas. These data were not used in the model fits since this laborious hand collection of data was done on only a few canopies. The F-22 canopies were measured on a modified system at Sierracin/Sylmar Corp by University of Dayton Research Institute personnel.

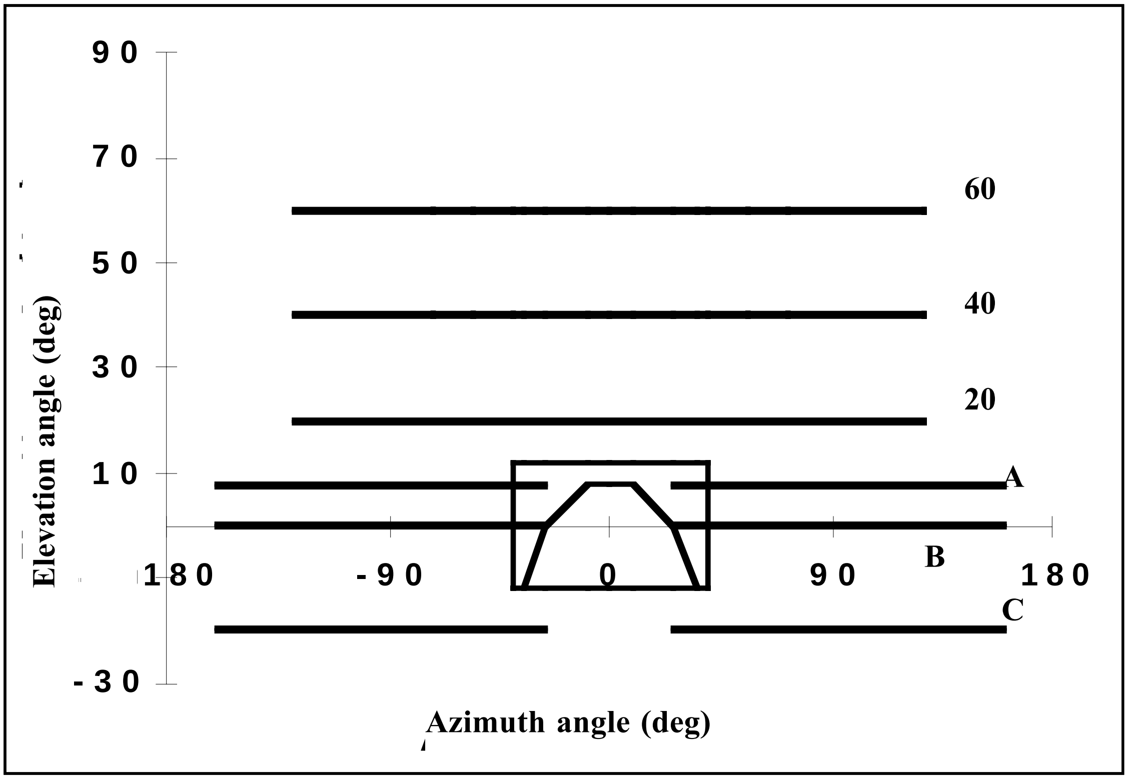

Figure 1. Measurement zones (upper three dark lines & the box) for which data were collected.

Figure 2. Windscreen movement table and angular deviation measurement system set for measuring the box area.

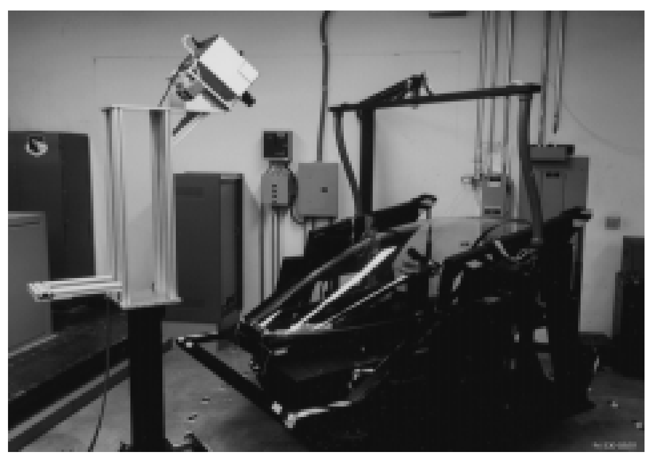

Figure 3. Measurement system set to measure 40 deg EL.

2.2 Model development

A "best fit" polynomial model was developed separately for the azimuth and elevation angular deviation data. The mean deviation of the measured transparencies was the dependent variable. A multi-variate regression procedure, that maximizes R^2, was used on the means for each fighter separately, for both the single and dual zone models. The terms used in the regression were az, az^2, az^3, az^4, az^5, az^6, el, el^2, el^3, x, y, and z (plus all meaningful 2-way interactions). The goal was to use R^2 values from models with 1-term, 2-terms, etc., to determine a single set of terms (coefficients would vary) that could be used across fighters and single/dual models. For the fit of azimuth and elevation means, there were 5 or 6 terms that appeared consistently in the models with the highest R^2. Determining which additional terms to use included but was not limited to: (a) all terms be significant, (b) don't add terms past the point where the increase in R^2 was "small", (c) if undecided, use terms that helped the F-16 and F-22 more since they had the largest uncorrected RMS.

2.3 Model evaluation

The residual (after model applied as a correcton) root-mean-square (RMS) error was used as the primary metric in determining how good the model fit the data. The RMS value was calculated using equation 1:

$$\text{RMS} = \sqrt{\frac{\sum V^2}{N}} \qquad (1)$$

where: RMS = root-mean-square

N = number of points involved in calculation

$V^2 = (DAZ - pDAZ)^2 + (DEL - pDEL)^2$

and

DAZ=measured azimuth angular deviation (for each point)

DEL= measured elevation angular deviation (for each point)

pDAZ= "predicted" (by the model) azimuth angular deviation

pDEL= "predicted" (by the model) elevatn angular deviation.

In order to calculate a baseline error the RMS value was calculated using zero as the reference or "predicted" values of angular deviation (this is the RMS-U column in Table 3). The manufacturing variation was determined by calculating the RMS value using the mean across transparencies as the predicted value (this is the RMS-M column in Table 3). The RMS values for the two "best fit" models (single-zone and dual zone models) were calculated with the predicted values coming from the models (these are the RMS-S and RMS-D columns in Table 3). To further investigate the goodness of fit of these models the RMS values were calculated for the entire transparency as well as for the various elevation angles at which data was collected. These results are summarized in Table 3.

3. RESULTS

3.1 Dual-zone model

A comprehensive model was developed which describes the angular deviation for each aircraft (F-15, F-16, F-18, and F-22) throughout the angle space that could be measured. The following tables present the coefficients for each term (variable) and each aircraft. Figure 4 shows the angle space over which the model is valid. Referring to Figure 4, the upper zone ranges from +8 degrees elevation to +90 degrees elevation and the lower zone ranges from -12 degrees elevation to +8 degrees elevation. At 8 degrees elevation the curves generated by the two sets of coefficients in Tables 1a and 1b are sufficiently similar that there should be no significant discontinuity between them as one transitions from the lower zone to the upper zone. The following restrictions and guidelines apply to this model:

1. The model describes the angular deviation present, <u>NOT</u> the correction required.
2. The model is only valid for the eye motion box measured.

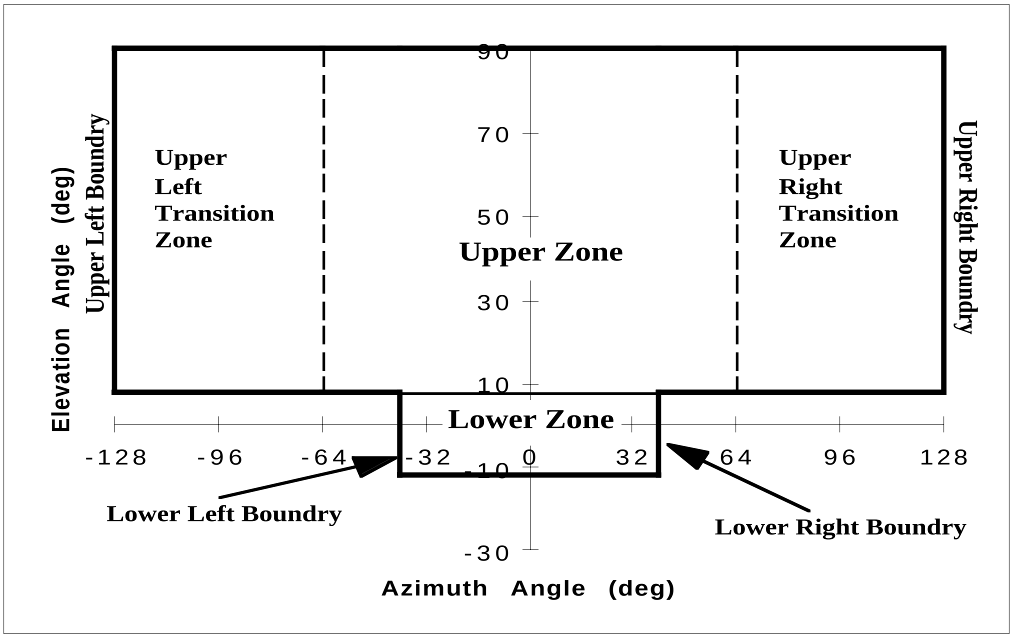

Figure 4. Zones in angle space over which the dual-zone angular deviation fit model is valid.

Symbols:

X = x = fore-aft direction (inches)
Y = y = left-right direction (inches)
Z = z = up-down direction (inches)

AZ = az = azimuth angle (degrees)
EL = el = elevation angle (degrees)
AZC = azimuth correction (mrad)
ELC = elevation correction (mrad)

Table 1a. Terms and coefficients of dual zone model for deviation in elevation.

	Coefficients for Lower Zone				Coefficients for Upper Zone			
Term	**F-15**	**F-16**	**F-18**	**F-22**	**F-15**	**F-16**	**F-18**	**F-22**
Intercept	0	0	0	0	-9.02E-01	5.71E+00	-2.51E+00	8.24E+00
az^2	8.68E-03	1.18E-02	2.44E-03	1.02E-03	1.02E-03	1.08E-03	1.06E-03	-1.08E-03
az^4	-5.86E-06	-9.73E-06	-1.77E-06	-1.88E-07	-9.08E-08	-9.12E-08	-8.07E-08	1.04E-07
az^6	1.04E-09	2.85E-09	3.11E-10	7.97E-12	2.16E-12	2.29E-12	1.53E-12	-3.26E-12
el	2.04E-03	3.76E-01	-2.14E-01	4.23E-01	-4.72E-03	-9.05E-02	2.55E-02	-1.34E-01
z	2.70E-01	1.41E+00	9.35E-02	1.89E+00	2.17E-01	8.14E-01	2.39E-01	1.30E+00
$az*y$	8.86E-03	3.47E-03	1.36E-02	1.61E-03	2.10E-03	8.65E-03	2.17E-03	8.58E-03
az^2*el	-3.19E-04	-5.93E-04	-5.89E-05	-4.78E-05	-6.00E-06	-4.52E-06	-8.74E-06	2.22E-05
az^4*el	9.98E-08	2.41E-07	5.17E-08	3.10E-09	3.88E-10	1.67E-10	4.99E-10	-1.13E-09
N	750	792	633	1139	1115	1116	1116	1788
R^2	0.87	0.95	0.48	0.64	0.84	0.88	0.75	0.76

Table 1b. Terms and coefficients of dual zone model for deviation in azimuth.

	Coefficients for Lower Zone				Coefficients for Upper Zone			
Term	**F-15**	**F-16**	**F-18**	**F-22**	**F-15**	**F-16**	**F-18**	**F-22**
az	-2.29E-01	-1.28E-01	-1.87E-01	7.53E-02	-5.25E-02	-4.75E-02	-4.99E-02	2.65E-03
az^3	1.61E-04	7.24E-05	1.16E-04	-2.91E-05	7.48E-06	5.53E-06	6.57E-06	-2.21E-06
az^5	-3.11E-08	9.32E-10	-2.09E-08	1.71E-09	-2.34E-10	-1.71E-10	-1.82E-10	1.50E-10
y	-6.92E-01	-8.75E-01	-5.06E-01	-1.14E+00	-1.97E-01	-8.23E-01	-2.38E-01	-9.90E-01
$az^2 * y$	2.15E-04	2.45E-04	1.83E-04	4.30E-04	1.20E-05	8.12E-05	1.65E-05	1.04E-04
$az * el$	-2.10E-03	3.10E-03	-3.38E-03	3.17E-03	1.98E-04	1.13E-04	2.11E-04	-4.44E-04
$az^3 * el$	3.11E-07	-5.73E-06	1.09E-06	-1.86E-06	-2.17E-08	9.99E-09	-2.49E-08	4.17E-08
N	750	792	633	1139	1115	1116	1116	1788
R^2	0.95	0.87	0.80	0.74	0.87	0.90	0.84	0.69

3.2 Implementation of the dual-zone model

Table 3 and the last rows of Tables 1a and 1b describe how well the dual-zone model fits the data. This section is to clarify the way in which the model needs to be implemented and how to treat the transition areas at the boundary between upper and lower zones and at the Azimuth angle boundaries for the upper and lower zones (see Figure 4). The logical sequence for model implementation is:

1. Determine aircraft type (this establishes the correct set of coefficients)
2. Determine if the eye position is outside of the allowed motion box. If it is, then set eye position coordinates to the nearest edge of the box. The eye motion box coordinate system is set for zero at the aircraft design eye position. The X coordinate is fore-aft with forward being positive, the Y coordinate is left-right with left being positive, and Z is up-down with up being positive. The limits of the box are X=0 to X=+2 inches, Y=+1.75 to -4.25 inches, and Z=0 to +2 inches. The logic sequence for determining values of position for angular deviation correction are (note that X is not used in any of the variables in the model so its value is irrelevant for correction calculation):
   2a. If Y<-4.25 then Y= -4.25, if Y>1.75 then Y=1.75
   2b. If Z<0 then Z=0, if Z>2 then Z=2
3. Determine upper or lower zone:
   3a. If elevation angle (EL) is less than -12 degrees then AZC and ELC (corrections) equal zero.
   3b. If EL is in the range of -12 through +8 then use the coefficients for the lower zone.
   3c. If EL is greater than +8 degrees then use the coefficients for the upper zone.
4. Upper zone Azimuth boundary treatment (for ALL 4 aircraft):
   4a. For AZIMUTH correction: if AZ>128 then AZ=128, if AZ<-128 then AZ=-128.
   4b. For ELEVATION correction: if AZ>64 then AZ=64, if AZ<-64 then AZ=-64.
5. Lower zone Azimuth boundary treatment for ELEVATION CORRECTION:
   5a. For F-15 & F-18: If AZ>40 or if AZ<-40 then AZC = ELC=0 (no corrections)
   5b. For F-16 & F-22: If AZ>40 then AZ=40, if AZ<-40 then AZ=-40.
6. Lower zone Azimuth boundary treatment for AZIMUTH CORRECTION:
   For ALL aircraft if AZ>40 or if AZ<-40 then AZC=ELC=0 (no corrections)

3.3 Single-zone model

A single-zone model was developed as a "best fit" to the angular deviation for each aircraft throughout the appropriate angle space that was a subset of the angle space that could be measured using the available modified equipment. Tables 2a and 2b contain the coefficients for each term (variable) and each aircraft. The single-zone over which this model is valid differs from aircraft to aircraft. The following restrictions and guidelines apply to this model:

1. The model describes the angular deviation present, <u>NOT</u> the correction required.
2. The model is only valid for the eye motion box measured.

Table 2a. Terms and coefficients of single zone model for deviation in elevation.

	Coefficients			
Term	**F-15**	**F-16**	**F-18**	**F-22**
Intercept	1.30E+00	1.51E+00	5.88E-01	7.17E+00
az^2	1.42E-03	2.81E-03	9.46E-05	-9.73E-04
az^4	-1.62E-07	-2.31E-07	-1.60E-08	9.70E-08
az^6	4.46E-12	4.85E-12	9.37E-13	-3.36E-12
el	-6.15E-02	-9.00E-04	-4.61E-02	-1.12E-01
z	2.86E-01	1.06E+00	2.31E-01	1.41E+00
az∗y	3.62E-03	8.27E-03	4.23E-03	7.73E-03
az^2∗el	-7.46E-06	-3.70E-05	1.20E-05	1.95E-05
az^4∗el	7.52E-10	2.02E-09	-6.75E-10	-9.24E-10
N	1865	1908	1749	2099
R^2	0.49	0.70	0.29	0.64

Table 2b. Terms and coefficients of single zone model for deviation in azimuth.

	Coefficients			
Term	**F-15**	**F-16**	**F-18**	**F-22**
az	-1.07E-01	-4.70E-02	-8.49E-02	2.38E-02
az^3	1.29E-05	6.61E-06	1.08E-05	-5.72E-06
az^5	-3.39E-10	-2.25E-10	-3.18E-10	2.93E-10
y	-4.98E-01	-8.09E-01	-3.96E-01	-8.29E-01
az^2∗y	4.70E-05	8.28E-05	3.89E-05	8.53E-05
az∗el	1.22E-03	-2.11E-05	7.62E-04	-7.19E-04
az^3∗el	-9.72E-08	1.27E-08	-6.08E-08	6.96E-08
N	1865	1908	1749	2099
R^2	0.79	0.76	0.73	0.65

3.4 Implementation of the single zone model

The preceding tables list the coefficients of the variables for the single zone model for all four aircraft. This section is to clarify the way in which the model needs to be implemented and how to treat the transition areas at the Azimuth angle boundaries for the upper and lower portions of the single correction zone and the upper and lower Elevation angle boundry of the single correction zone. Symbol definitions:

Symbols: X = x = fore-aft direction (inches) AZ = az = azimuth angle (degrees)

Y = y = left-right direction (inches)   EL = el = elevation angle (degrees)
Z = z = up-down direction (inches)   AZC = azimuth correction (mrad)
ELC = elevation correction (mrad)

The logical sequence for model implementation is:

1. Determine aircraft type (this establishes the correct set of coefficients and the lower boundry to the correction zone)
2. Determine if the eye position is outside of the allowed motion box. If it is, then set eye position coordinates to the nearest edge of the box. The eye motion box coordinate system is set for zero at the aircraft design eye position. The X coordinate is fore-aft with forward being positive, the Y coordinate is left-right with left being positive, and Z is up-down with up being positive. The limits of the box are X=0 to X=+2 inches, Y=+1.75 to -4.25 inches, and Z=0 to +2 inches. The logic sequence for determining values of position for angular deviation correction are (note that X is not used in any of the variables in the model so its value is irrelevant for correction calculation):
    2a. If Y<-4.25 then Y= -4.25, if Y>1.75 then Y=1.75
    2b. If Z<0 then Z=0, if Z>2 then Z=2
3. Determine upper or lower portion of single correction zone:
    3a. For F-15, F-16, and F-18: if elevation angle (EL) is less than -12 degrees then AZC and ELC (corrections) equal zero.
    3b. For F-22: if EL<+5 degrees then AZC and ELC equal zero.
    3c. If EL is greater than +70 degrees then EL=70.
    3d. If EL is greater than +8 but less than +70 degrees then see #4 for Azimuth bound.
    3e. For F-15, F16, F-18 if EL is greater than -12 but less than +8 then see #5 & #6 for Azimuth bound.
    3f. For F-22 if EL is greater than +5 but less than +8 then see #5 & #6 for Azimuth bound.
4. Upper portion of single zone Azimuth boundary treatment (+8<EL<70; for ALL 4 aircraft):
    4a. For AZIMUTH correction: if AZ>128 then AZ=128, if AZ<-128 then AZ=-128.
    4b. For ELEVATION correction: if AZ>64 then AZ=64, if AZ<-64 then AZ=-64.
5. Lower zone Azimuth boundary treatment for ELEVATION CORRECTION:
    5a. For F-15 & F-18: If AZ>40 or if AZ<-40 then AZC = ELC=0 (no corrections)
    5b. For F-16 & F-22: If AZ>40 then AZ=40, if AZ<-40 then AZ=-40.
6. Lower zone Azimuth boundary treatment for AZIMUTH CORRECTION:
    For ALL aircraft if AZ>40 or if AZ<-40 then AZC=ELC=0 (no corrections)

3.5 Residual errors

Table 3 is a comprehensive listing of the root-mean-square (RMS) errors for angular deviation referenced to different values. RMS-U is the RMS error referenced to zero (no correction), RMS-M is the RMS error referenced to the mean angular deviation value (at each az and el angle) of the transparencies measured, RMS-S is the RMS error referenced to the single-zone best fit model (described later) and RMS-D is the RMS error referenced to the dual-zone fit model (also, described later).

In Table 3 the numbers under the column with an "N" at the top are the number of data points that were used to calculate the RMS for each elevation angle. The number of data points include data taken from all 12 eye positions and all azimuth angles that could be measured. The RMS-U values indicate how much angular deviation was present in the transparencies measured. The RMS-M values are an indication of how much manufacturing variation there is within each transparency (and elevation angle). This is important in that no model developed to be generic to the aircraft type (e.g. F-15) can reduce the error any further than this value since it represents the variation in angular deviation from transparency to transparency due simply to manufacturing variations. The last two columns of Table 3 are discussed in more detail in the following section. These two columns are an indication of how well the single-zone and dual-zone models fit the angular deviation data. In general, the dual-zone model provides a somewhat better fit to the measured data than does the single-zone model but neither one of them fits so well that all that is left is the manufacturing variation (but the dual-zone model comes pretty close).

Table 3. RMS Errors (milliradians) by elevation angle

Fighter	El (deg)	N	RMS-U	RMS-M	RMS-S	RMS-D
F-15	60	1488	1.3	0.4	1.2	0.7
	40	1484	1.9	0.3	0.7	0.7
	20	1488	2.4	0.5	1.8	0.9
	8	144	3.9	1.2	2.2	2.0
	4	336	4.2	0.9	2.1	1.2
	0	732	4.6	0.9	2.3	1.3
	-4	954	4.8	0.9	2.4	1.3
	-8	1122	5.3	0.8	2.7	1.4
	-12	1212	5.4	0.8	3.0	1.6
	Total	8960	3.8	0.7	2.1	1.2
F-16	60	2232	3.9	0.7	1.7	1.4
	40	2232	5.9	0.8	1.5	1.5
	20	2232	7.5	1.0	1.9	1.6
	8	792	6.9	1.4	2.7	1.8
	4	792	6.8	1.5	2.4	1.8
	0	792	6.4	1.8	2.4	2.0
	-4	792	6.0	2.1	2.9	2.2
	-8	792	5.6	2.1	3.6	2.4
	-12	792	5.6	2.2	4.5	2.7
	Total	11448	6.1	1.4	2.4	1.8
F-18	60	1860	1.7	0.6	1.0	0.9
	40	1860	1.9	0.7	0.9	1.0
	20	1860	2.4	0.8	1.6	1.3
	8	439	3.4	1.0	3.0	2.6
	4	477	3.7	1.2	2.9	2.5
	0	489	4.2	1.2	3.1	2.6
	-4	531	4.5	1.2	3.3	2.8
	-8	550	4.7	1.2	3.5	2.8
	-12	523	5.0	1.6	4.0	3.0
	Total	8589	3.0	0.9	2.2	1.8
F-22	60	1392	4.5	0.6	2.3	2.0
	40	1392	5.8	0.7	2.1	1.9
	20	1425	7.1	0.8	2.1	1.9
	15	720	7.4	0.7	2.1	2.0
	10	1488	6.8	0.9	2.2	2.4
	5	622	5.9	0.6	3.2	2.0
	0	1200	4.3	0.9		2.3
	-5	504	3.4	0.6		2.5
	-10	1104	2.7	1.0		2.5
	Total	9847	5.6	0.8		2.2
	Total (≥5°)	7039	6.3	0.7	2.3	2.1

RMS-U = Deviation from 0 (Uncorrected)
RMS-M = Deviation from Mean of Measured Transparencies
RMS-S = Deviation from Single Zone Model
RMS-D = Deviation from Dual Zone Model

4. DISCUSSION

The original objective of this effort was to develop a single, "simple" algorithm that could be used to correct for as much angular deviation error as possible for all four aircraft types. Ideally, the algorithm would be an unbounded polynomial that would do a reasonable job of correcting the angular deviation for all view angles, eye positions, and aircraft type. After looking at the shape of angular deviation curves obtained for each aircraft and the attempts at multi-variate linear regression to get a good fitting polynomial, it was apparent that a better fit could be obtained if the view angles were divided into zones. This led to the "dual-zone" model with boundaries. The polynomial coefficients are different for the two zones (see Tables 1a and 1b) in order to better fit the empirical data. Boundary conditions were established because the polynomial fit (for both single-zone and dual-zone models) would "blow up" in areas (view angles) outside of the view angles that were measured. This would actually introduce aiming error instead of correcting for existing angluar deviation so rules had to be established for treating the correction algorithm outside of the established zones. These rules are presented under the Results section for each model.

Both single-zone and dual zone models were developed using only the angular deviation data collected at the lines marked 20, 40, and 60 (degrees) and in the central box of Figure 1. These data were collected using the automated angular devation measurement system (Figures 2 and 3) and correspond to the maximum possible view angle range that this system could measure. However, a crude, hand-moved table was constructed to manually collect a limited amount of data on one transparency of each type (except F-22) to validate the rules developed for treating angular deviation at the boundaries of the zones over which the algorithms were valid. These data were collected at view angles indicated by the lines on Figure 1 labeled A, B, and C. In general, these view angles were blocked on the automated system by the A-frame structure on each side designed to support the table.

Table 4 is a summary of the root-mean-square (RMS) data for each aircraft type. The column labeled "uncorrected" is the overall value of RMS angular deviation (for angles and eye positions measured) for each aircraft transparency system. This value was calculated by using "zero" as a reference for each point. The column labeled "manufacture" is the overall RMS value of each aircraft transparency system using the average (at each point) of the transparencies measured as the reference point. This represents the variation in transparencies due to manufacturing and should be considered the best obtainable correction assuming our small sample is representative of the transparencies currently manufactured. The columns labeled "Single Z" and "Dual Z" are the RMS values calculated using the single-zone model and dual-zone model (respectively) as the reference points. Note that the value listed for the F-22 is for view angles of 5 degrees elevation and higher (see Table 3). It is apparent from Table 4 that both the single-zone and dual-zone models significantly reduce residual angular deviation and that the dual-zone model is consistantly better than the single-zone model, although, in some cases, not by very much.

Table 4. RMS Errors (milliradians) Summary

Fighter	**uncorrected**	**manufacture**	**Single Z**	**Dual Z**
F-15	3.8	0.7	2.1	1.2
F-16	6.1	1.4	2.4	1.8
F-18	3.0	0.9	2.2	1.8
F-22	6.3	0.7	2.3	2.1

5. CONCLUSIONS

It should be noted that there are essentially an infinite number of models that could be developed that would correct for aircraft transparency angular deviation to some extent. This effort has explored one approach to this problem and developed two models that provide a significant improvement over the uncorrected condition. It is possible that better corrections could be obtained by doing piece-wise modeling, using other than a polynomial for the model, or by measuring and custom correcting each transparency as is done for the F-16 HUD.

Future work in this area should concentrate on making measurements from a significantly increased eye/head motion box and a wider range of view angles.

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